Estimation of soil erosion in burnt forest areas of the Cerro Grande Fire in Los Alamos, New Mexico

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Abstract

Two methods were used to estimate wildfire-induced surface soil erosion hazards for the Cerro Grande Fire that occurred in 2000 in northern New Mexico. The first was the method commonly used by the Interagency Burned Area Emergency Rehabilitation (BAER) Team, and was the method used by the BAER Team on the Cerro Grande Fire. In this method, pre-fire Universal Soil Loss Equation (USLE) estimates of soil loss, published in the Terrestrial Ecosystem Surveys of the Santa Fe National Forest, were multiplied by five factors to account for burn severity and hydrophobic soils to obtain post-fire soil erosion estimates. The second method (Enhanced USLE Approach) involved making estimates of soil erosion that incorporated several precipitation zones and estimates of changes in ground and canopy cover. The Enhanced USLE Approach allowed for a more cost-effective spatial resolution of conservation measures to be applied to burned areas, potential improvements on the methods that future BAER Teams can use, and an improved evaluation of the kind of information that should be in a facility's natural resources database.

Keywords: Burned Area Emergency Rehabilitation; Conservation; Erosion; Forest fire effects; Hydrologic modeling; Soil erosion models; USLE

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1. Introduction

The East Jemez Region has experienced two major wildfires in the previous five years, as well as the recent Cerro Grande Fire in 2000. The recurrence of broad-scale wildfires in this region has been estimated at once every ten years, and post-fire soil erosion and storm water runoff can result in contaminant transport and flooding of downstream facilities. Identification of potential problem areas will allow us to design and implement mitigation actions to protect our lives, as well as our environment and facilities.

The La Mesa Fire of June 1977 burned across 6,250 ha (15,444 A) of land in and around Bandelier National Monument near Los Alamos, New Mexico, and resulted in two symposiums on fire research (Foxx, 1984; Allen, 1996). The Dome Fire was ignited in April 1996 and burned 6,684 ha (16,516 A) of federal lands (US Department of Interior (DOI), 1996). Although this fire impacted other canyons, the effects of the fire were particularly severe in the Boundary Peak and Capulin Canyon areas, where the responses of the drainage basins were compared to identify characteristics that indicate a susceptibility to wildfire-related debris flow (Cannon and Reneau, 2000). The Universal Soil Loss Equation (USLE) was used to evaluate soil erosion in a small portion of the Los Alamos National Laboratory before the Cerro Grande Fire occurred in 2000 (Loftin et al., 2000). Previous studies evaluated the USLE for the prediction of soil erosion in 29 forested plots in northwestern Spain, all of which suffered forest fires during the period 1979–1982 (Diaz-Fierros et al., 1987). Various factors influencing soil erodibility were studied in a grassland area of the humid tropics subject to frequent wildfires (Ternan and Neller, 1999). The revised USLE was integrated with a Geographic Information Systems (GIS) format to model erosion potential for soil conservation planning in a region in Mexico with mountainous topography and a tropical unimodal precipitation regime (Millward and Mersey, 1999).

The current study compares two methods for estimating wildfire-induced surface soil erosion hazards to make rehabilitation plans for burnt forest areas more cost-effective. The first method is the one commonly used by the Interagency Burned Area Emergency Rehabilitation (BAER) Team and which they used for the Cerro Grande Fire. In this method, pre-fire USLE estimates of soil loss, found in the Terrestrial Ecosystem Surveys of the Santa Fe National Forest, were extrapolated to all of the soils found within the areas affected by the fire. These initial soil loss estimates were then multiplied by five factors to account for the effects of burn severity and hydrophobic soils to obtain post-fire soil erosion estimates. The second method (Enhanced USLE Approach) involved making estimates of soil erosion that incorporated a multitude of precipitation zones varying with elevation and field estimates of changes in ground and canopy cover for several habitat types.

2. Materials and Methods

Soil erosion was initially estimated using a DOI BAER standard technique (Interagency Burned Area Emergency Rehabilitation Team, 2000). A second approach involved an enhancement of a standard US Department of Agriculture (USDA) technique (Wischmeier and Smith, 1978), using field estimates of ground and canopy cover and solving the USLE for each 900-m^2 GIS cell throughout the burned area.

2.1 Description of the study area

The land surrounding Los Alamos is largely undeveloped, and large tracts of land north, west, and south of the Laboratory site are held by the Santa Fe National Forest, Bureau of Land Management, Bandelier National Monument, General Services Administration, Los Alamos County, and Santa Clara and San Ildefonso Pueblos. The city of Los Alamos and the Los Alamos National Laboratory (LANL) are situated on the

Pajarito Plateau at the base of the headwater basins draining from the Jemez Mountains (Fig. 1). The fire directly affected portions of the city and the Laboratory, destroying or damaging 235 residential structures in Los Alamos and 112 structures at the Laboratory (Site-Wide Issues Program Office, 2000), as well as over 47,650 acres of forestland (Cerro Grande Fire description at http://www.fs.fed.us/r3/sfe/fire/). The proximity of Los Alamos and LANL to these headwater basins defines a wildland-urban interface with greatly increased potential for storm flow and flooding, particularly in watersheds with a large percentage of high burn severity that will have short reaction time between rainfall and storm flow runoff. More distant communities that have been affected by post-fire hydrologic events include White Rock and the Santa Clara and San Ildefonso Pueblos.

The Cerro Grande Fire occurred in the Sierra de los Valles on the eastern flank of the Jemez Mountains and on the western side of the Pajarito Plateau. Elevations of the burn area range from approximately 1,950 m (6,400 feet) to 3,140 m (10,300 feet). All burned watersheds drain eastward/southeastward to the Rio Grande upstream of Cochiti Reservoir. The Sierra de los Valles contains the headwaters of most burned watersheds and is dominated by steep rugged terrain underlain by dacitic rocks of the Miocene-Pliocene Tschicoma Formation, occupying about 22% of Los Alamos County. The Pajarito Plateau consists of gently sloping mesas and steep-sided canyons underlain by the early Pleistocene Bandelier Tuff, which occupies about 63% of Los Alamos County and contains both welded and nonwelded tuffs that vary in their resistance to long-term weathering.

Of the 10 recognized soil orders, only five exist in the Los Alamos area: Alfisols, Aridisols, Entisols, Inceptisols, and Mollisols. About 80% of the county soils can be grouped into the Alfisol, Entisol, and Mollisol soil orders (Nyhan et al., 1978). About 20% of the county contains rock outcrop mapping units, and 38% of the county contains soil complexes with rock outcrop members. In terms of landform characteristics (Interagency Burned Area Emergency Rehabilitation Team, 2000), dissected piedmont plains with 15–25% slopes contained Haploxeroll and Haplustalf soil subgroups. Foothills and mountain slopes contained predominantly ponderosa pine, slopes of 20–55%, and Ustochrept, Ustorthent, and Haplustalf soil subgroups. However, 34% of the Cerro Grande Fire area was dominated by subalpine basins and mountain ridges with slopes ranging from 40 to >65%, which contained Cryochrept, Dystrochrept, Eutroboralf, and Glossoboralf soil subgroups.

2.2 *Estimation of soil erosion*

The BAER team used site indicators to evaluate burn severity (Interagency Burned Area Emergency Rehabilitation Team, 2000). The mapping criteria included soil hydrophobicity (water repellency), ash depth and color (fire severity), size of residual fuels (fire intensity), soil texture and structure, and post-fire effective ground cover. These criteria indicate fire residence time, depth of litter layer consumed, radiant heat throughout the litter layer, and ease of detachability of the surface soil. Using these indicators and digital color infrared imagery acquired on May 20–21, 2000, the team field surveyed and mapped the burned area into three relative burn severity categories: high, moderate, and low/unburned, which contained 5,872 ha, 1,344 ha, and 10,131 ha (14,511 A, 3,323 A, and 25,035 A), respectively.

After the field examination of the burn severity and soil response and based upon past soil erosion events following wildfire in similar soils, the BAER team adjusted the USLE erosion rates from the Santa Fe National Forest (Terrestrial Ecosystem Survey—TES) in the following manner:

(1) For soils mapped as low/unburned, the USLE soil erosion rates for current conditions were multiplied by a fire correction factor of 1.1.
(2) For soils with moderate burn severity, the USLE soil erosion rate for potential erosion was multiplied by a fire correction factor of 0.75.
(3) For soils on northerly and southerly aspects with high burn severity and vegetation/aspect sites that did not exhibit hydrophobic soil conditions, the USLE potential erosion rate was used.
(4) For the 3,768 ha (9,310 A) of hydrophobic soils found in the 14,111 acres of the high burn severity category (US Department of Energy, National Nuclear Security Administration, 2000), the USLE potential erosion rate was multiplied by a USLE Potential Soil Erosion Rate factor (Table 1).

The Enhanced USLE approach involved solving all the factors of the USLE model (Wischmeier and Smith, 1978), expressed as:

$$A = (R)\,(K)\,(LS)\,(C)\,(P) \tag{1}$$

where
A, the computed loss per unit area, is expressed in the units selected for K and for the period selected for R;
R, the rainfall runoff factor, is the number of rainfall erosion index units plus a factor for runoff from snowmelt or applied water where such runoff is significant;
K, the soil erodibility factor, is the soil loss rate per erosion index unit for a specified soil as measured on a unit plot, which is defined as a 22.1-m (72.6-ft) length of uniform 9% slope continuously in clean-tilled fallow;
L, the slope-length factor, is the ratio of soil loss from the field slope length to that from a 22.1-m (72.6-ft) length under identical conditions;
S, the slope-steepness factor, is the ratio of soil loss from the field slope gradient to that from a 9% slope under otherwise identical conditions;
C, the cover management factor, is the ratio of soil loss from an area with specified cover and management to that from an identical area in tilled continuous fallow; and
P, the support practice factor, is the ratio of soil loss with a support practice like contouring, strip-cropping, or terracing to that with straight-row farming up and down the slope.

2.3 *Data sources*

2.3.1 Estimation of precipitation and the R Factor

Because annual rainfall and, thus the value of the R Factor, increases with elevation (Nyhan and Lane, 1986; Wischmeier and Smith, 1978), an R Factor GIS data layer was developed for use with the USLE approach. The first step in this process involved determining how rainfall increased with elevation in the Los Alamos environs (Bowen, 1990; Daly et al., 1998) and digitizing this data. This annual precipitation map was compared with similar data developed from National Oceanic and Atmospheric Administration (NOAA) Cooperative Stations and USDA National Resource Conservation Service (NRCS) Snowpack Telemetry (SNOTEL) stations (Oregon Climate Service, 1998). We determined a regression relationship between annual precipitation and the 2-yr, 6-hour rainfall (P) from local meteorological data (Bowen, 1990) and estimated R Factor values from P using equation (2), according to methods described previously (Wischmeier and Smith, 1978; Nyhan and Lane, 1986).

$$R = (27.38)\,(P^{2.17}) \qquad (2)$$

2.4 Soil surveys and the K Factor

To assess some of the potential effects of the wildfire on the soil resource, a soil survey GIS data layer was developed. This map was a composite of the soil surveys of Los Alamos National Laboratory (Nyhan et al., 1978), Santa Fe National Forest (Miller et al., 1993), Santa Fe (Folks, 1975), Rio Arriba (Roybal, 1991), and Bandelier National Monument (Earth Environmental Consultants Incorporated, 1974). Each of these surveys contained estimates of the K Factor, which was estimated from the amounts of silt, very fine sand, clay, soil organic matter, soil structure, and soil profile permeability for each soil (Nyhan and Lane, 1986; Wischmeier and Smith, 1978). Field determinations of the K Factor were shown to agree well with K Factor values estimated in this way (Nyhan et al., 1984).

The TES of the Santa Fe National Forest (Miller et al., 1993) has USLE erosion rates calculated for three conditions: natural conditions (minimum rates associated with a climax vegetation class), current conditions (rate of soil loss occurring under conditions associated with existing groundcover conditions), and potential conditions (maximum erosion following complete removal of the vegetation and the litter from a site).

The soil map units for the other soil surveys within the burn area were correlated to the Santa Fe National Forest map units. This correlation allowed linking locally developed USLE estimated soil erosion rates (for various soil conditions) to all the soil map units in the burn area.

The development of the BAER pre-fire and post-fire soil erosion estimates required knowledge of the response of the soils to the wildfire. The unburned areas examined displayed some slight to moderate water repellency, which is not unusual for surface soils that are high in organic matter and are very dry. Waxy organic compounds from the duff, especially when dry, often affect surface tension and can cause light scattered water repellency if the surface duff is removed. Heat from an intense wildfire can volatize these compounds and drive the gases into the mineral soil; upon cooling, they recondense and coat soil particles, increasing water repellency (see reviews by DeBano, 2000a, 2000b).

2.4.1 Estimation of the Slope Length and Steepness Factor (LS Factor)

The L Factor accounts for increases in runoff volume as downslope runoff lengths increase. The value of L was set at 30 m (99.69 ft), the size of each GIS cell. The slope steepness factor, S, accounts for increased runoff velocity as slope steepens and was calculated with the topographic data for the surrounding cells. For direct application in the USLE, the LS Factor was evaluated for each cell as (Wishmeier and Smith, 1965; Molnar and Julien, 1997):

$$LS = (99.69\ \text{ft})^{0.5}\ (.0076 + (0.0053)(\%\ \text{slope}) + (0.00076)\ (\%\ \text{slope})^{2}) \qquad (3)$$

2.4.2 Field estimates of vegetative cover and the C Factor

In the BAER approach, the C Factor was estimated by using average canopy cover estimates for various habitat types in each soil mapping unit area.

Using the Enhanced USLE approach, a 1992 Landsat thematic mapper image was classified into 30 classes using an Iterative Self-Organizing Data Analysis Technique. These classes were aggregated into 10 land cover or habitat types through field surveys, aerial photo interpretation, and the incorporation of topographic information (Koch et al., 1997). Using a nested, randomized plot layout and sampling design, macroplots (consisting of a square area, 60 m on each side) were selected in these habitat types (Balice et al., 2000). GPS data were collected for each macroplot and corrected using a base station and Pathfinder software (Trimble Navigation Ltd. 1995). Each macroplot consisted of four subplots (30 m on each side), and each subplot consisted of four quads (15 m on a side). One quad contained two 3-m by 15-m strip plots, which were used as vegetation and fuels transects, respectively.

The line intercept method was used to sample herbs, graminoids, shrubs, litter, duff, moss, lichens, cobbles, stones, boulders, bedrock, and bare soil (Canfield, 1941). Total ground cover was calculated by subtracting bare soil cover from 100%. Overstory trees and shrubs were defined as those that were at least 3.0 m (10 ft) tall, and overstory canopy cover was estimated using the densiometer method (Lemmon, 1956).

In the Enhanced USLE approach, the C Factor was estimated from the ground and canopy cover estimates using C values recommended for permanent pasture, rangeland, and idle lands (Wischmeier, 1974). This approach allows prediction of C Factors as functions of the type and height of plant canopy, their canopy cover, and the corresponding ground cover of compacted duff and vegetation, as demonstrated in Fig. 2. Several of these Wischmeier models were then matched up to our habitat types, and regression equations were used to predict the C Factor for each habitat type.

To assess the effects of the Cerro Grande Fire on C Factor values, we then assumed that the following reductions in ground and canopy cover occurred for each of the three relative burn severity categories and developed a data layer for this GIS coverage for each habitat type: High severity: 95% reduction, Moderate severity: 50% reduction, and Low/Unburned severity: 5% reduction.

2.4.3 The P Factor

Exact estimates of the effectiveness of BAER soil erosion prevention treatments are currently unknown for the Cerro Grande Fire. However, the effectiveness of the conservation measures has been estimated at other burned sites where they were applied; these measures usually reduce soil erosion from 15 to 30% (Robichaud et al., 2000).

3. Results and Discussion

3.1 The R Factor

A regression relationship between local annual precipitation (X) and the 2-yr, 6-hour rainfall (P) was determined as:

$$P = -0.475 + (0.1467)(X^{(0.5)(\ln X)}) \quad (4)$$

This regression model fit the data well ($R^2 = 0.996$, F statistic = 2070), with a standard error of only 0.516 MJ mm ha^{-1} h^{-1} yr^{-1} [0.0303 (hundreds of ft-T)(in) A^{-1} hr^{-1}yr^{-1}]. Equation 2 was then used to predict the R Factor values for seven annual precipitation zones (Table 2) across the elevation gradient within the areas burned by the Cerro Grande Fire. The R Factor varied from 594 to 2,178 MJ mm ha^{-1} h^{-1} yr^{-1} (35 to 128 (hundreds of ft-T)(in) A^{-1} hr^{-1}yr^{-1}) as annual precipitation ranged from 36 to 71 cm. The spatial distribution of this data across the Cerro Grande Fire area is shown in Fig. 3.

3.2 The K Factor

The K Factor for the soils in the Cerro Grande Fire area (Fig. 3) exhibited values of 0.0026, 0.0066, 0.0079, 0.0132, 0.0184, 0.0198, 0.0224, 0.0263, 0.0316, 0.0369, and 0.0487 (t) (ha) (h) ha^{-1} MJ^{-1} mm^{-1} (0.02, 0.05, 0.06, 0.10, 0.14, 0.15, 0.17, 0.20, 0.24, 0.28, and 0.37 (t)(A)(h) hundreds of acre-foot-tons^{-1} inch^{-1}). K Factor values for rock outcrop mapping units and paved parking lots occupied 9.5% of the area burned by the Cerro Grande Fire and were set equal to 0. For areas not containing rock outcrop, K Factor values increased for soils with increasing amounts of silt, very fine sand, and soil organic matter. Soils having K Factor values of 0.0132 and 0.0263 (t) (ha) (h) ha^{-1} MJ^{-1} mm^{-1} accounted for the two largest categories of soils, occupying 29.3 and 14.3% of the burned area. Soils with the largest K Factor values of 0.0487 (t) (ha) (h) ha^{-1} MJ^{-1} mm^{-1} occupied only 1.7% of the burned area.

3.3 The LS Factor (LS)

Because the LS Factor represents a ratio of soil losses, this factor is dimensionless and has a value of 1.0 for a 22.1-m (72.6-ft) uniform slope of 9%. Many locations on the mesa tops and a few high mountain meadows had LS Factor values (Fig. 3) less than 1.0, corresponding to slopes less than 9%. In Fig. 3, the LS Factor values of 3, 10, and 20 correspond to slopes of 17, 33, and 48%, respectively. Thus, the areas with LS Factor values greater than 3 correspond to the mountainous regions of the area, as well as the areas with steep canyon side slopes.

3.4 Field plot cover data and derivation of the C Factor

The Wischmeier models shown in Fig. 2 were matched up to our habitat types, and regression equations were used to predict the C Factor for each habitat type as functions of ground and canopy cover (Table 3). The three curvilinear regression models used fit the data very well (R^2 values usually equal to 1.00), exhibiting standard error values that were usually less than 0.63.

Before the Cerro Grande Fire, most of the field plots in the various habitat types had ground and canopy cover estimates in excess of 90% during 1998–1999 (Fig. 4). These cover estimates resulted in distributions of pre-fire values for the C Factor that were usually quite low, as opposed to after the Cerro Grande Fire (Fig. 5).

3.5 Erosion estimates

The US Environmental Protection Agency (EPA) recommends using a value of 4.5 t ha^{-1} yr^{-1} (2 t A^{-1} yr^{-1}) for tolerable soil loss rates (T) on disturbed soil systems (US EPA, 1989). However, in evaluating the long-term impact of soil erosion on wildfire-affected landscapes, these T values may be reasonable, especially because it is necessary to make assumptions about rates of soil formation, most of which have not been proven by research. However, Wight and Lovely (1982) point out that rangelands in arid and semiarid climates are inherently more fragile than eastern croplands and are characterized as having slow soil formation processes. They also indicated that even small increases in soil losses on rangeland could initiate accelerated soil erosion trends, because soil losses are accompanied by reduced production of protective vegetation.

We evaluated the BAER Team and Enhanced USLE methods of predicting soil erosion (Fig. 6). In view of the tolerable soil loss value discussed above, we regraphed the BAER Team estimates of soil loss, with this representing one of the categories of soil loss; the same approach was used with the Enhanced USLE method.

4. **Conclusions and Implications**

The final soil erosion estimates are presented for the BAER Team and Enhanced USLE Approaches for pre-fire (Fig. 6) and post-fire (Fig. 7) conditions. These GIS results are also summarized by watershed in Table 4.

For the pre-fire scenarios, the Enhanced USLE Approach exhibited twelve times less potential soil erosion within the perimeter of the Cerro Grande Fire than the BAER Team Approach (Fig. 6, Table 4). Most of the burned area contained tolerable soil loss rates of <4.5 t ha^{-1} yr^{-1} (<2 t A^{-1} yr^{-1}) using the Enhanced USLE Approach, with two exceptions. One exception was small areas in the lower elevations of all watersheds where the LS Factor had large values. The second exception was small areas in the upper elevations of all watersheds where both the LS and R factors had large values.

The maximum pre-fire soil erosion rates estimated for the BAER Team (Fig. 6) and Enhanced USLE Approaches were 278 and 184 t ha^{-1} yr^{-1} (124 and 82 t A^{-1} yr^{-1}), respectively. At lower elevations within the burn area the Enhanced USLE Approach estimated a few small areas with a soil loss rate of 4.5–278 t ha^{-1} yr^{-1} (2–124 t A^{-1} yr^{-1}, see Fig. 6), and these areas usually had similar values on the BAER Team map (Fig. 6). However, several areas at higher elevations within this erosion rate class showed up only on the Enhanced USLE map and not on the BAER map (Fig. 6).

There are several possible reasons why the BAER Team pre-fire estimates of soil erosion rates are generally much larger than those made by the Enhanced USLE Approach. One reason is that the BAER Team assumed that soil erosion rates had the same value across the entire area within each soil mapping unit; in the Enhanced USLE Approach, soil erosion rates were evaluated for each 30-m^2 cell. In addition, the BAER Team used ground and cover estimates made for the forest before 1993 (Miller et al., 1993), whereas these were estimated in the Enhanced USLE Approach from field data collected in 1998 and 1999 (Fig. 4, 5). This five-year difference could have meant at least another five years' growth of the forest, increasing ground and canopy cover and potentially reducing the soil erosion rates reported by the BAER Team. However, beyond this temporal effect, the techniques the BAER Team used to evaluate the relationships between soil erosion rates and canopy/ground cover (Miller et al., 1993) underestimated the magnitude of this effect (Fig. 2). Although the field techniques used to quantify ground and canopy cover are not documented (Miller et al., 1993), they were probably different than those used in this study.

The post-fire estimates of soil erosion are critical in applying soil conservation measures in the most cost-effective manner to avoid the loss of life and property, as well as further destruction of natural resources within and below the burned areas. The BAER Team estimated 7.5-fold more soil erosion after the Cerro Grande fire (Fig. 7, Table 4) than before the fire (Fig. 6, Table 4), taking into account canopy cover, ground cover, and hydrophobic soils (Table 1) effects. The Enhanced USLE Approach predicted that the Cerro Grande Fire could cause a 69-fold increase in soil erosion rates, only taking canopy cover and ground cover losses into account (Fig. 7, Table 4).

Because the BAER Team estimates involved multiplying soil erosion rates by the hydrophobic soil factors (Table 1), the BAER Team estimates of soil erosion rates across the entire burned area are 30% larger than similar Enhanced USLE values (Table 4). However, in spite of this difference, several areas were found with larger soil erosion rates using the Enhanced USLE Approach than those the BAER Team estimated (Fig. 7). Because the Enhanced USLE Approach predicted erosion rates as large as 7,551 t ha^{-1} yr^{-1} (3,368 t A^{-1} yr^{-1}), we arbitrarily choose two additional categories of soil loss rates: (1) 278–807 t ha^{-1} yr^{-1} (124–360 t A^{-1} yr^{-1}) and (2) 807–7,551 t ha^{-1} yr^{-1} (360–3,368 t A^{-1} yr^{-1}).

Burned areas containing these two categories of elevated soil erosion were always pinpointed within the 5,873 ha (14,511 A) of land with a high burn severity (see Fig. 5, post-fire C Factor estimates equal to 1).

The post-fire soil erosion rate results were compared to determine if large differences occurred between the two approaches to estimating soil erosion on a watershed basis (Table 4). After all, with similar data—such as the data layers for the K Factor and Topographic Factors (Fig. 3)—used in both approaches, the two approaches have some inherent similarities. Using the BAER Team estimates, the five watersheds with the largest soil erosion rates (presented in order of decreasing erosion rates) are Rendija, Guaje, Santa Clara, Los Alamos, and Pajarito Canyons. In comparison, the Enhanced USLE Approach exhibited a slightly different order for these same five watersheds: Los Alamos, Rendija, Guaje, Pajarito, and Santa Clara Canyons. Similar differences were found with the watersheds having the sixth through the tenth largest soil erosion rates. However, when it came to the watersheds with the eleventh through the sixteenth largest soil erosion rates, the results for both approaches gave exactly the same order (Table 4), with Frijoles Mesa watershed having the smallest soil erosion rate.

Empirical models such as the USLE tend to be easier to use because of the small number of input parameters required and have less potential for prediction errors to be introduced because of uncertainty in the model input values relative to physically based models (Nearing, 1998). Physically based models, such as the WEPP model, estimate the spatial and temporal distributions of soil loss, sediment yield, characteristics of sediment size, runoff volumes, soil water balance, and many other types of system information that the USLE cannot provide. The USLE was designed only to predict long-term, average annual soil loss. One should not expect the physically based, deterministic models to predict more accurately the rates of erosion from specific land areas.

With this caveat in mind, we need to realize that no published data exist on the relative effects of fire-induced water repellency in soils versus the loss of ground and canopy cover on increasing soil erosion after a forest fire. The contributions of fire-induced water repellency in soils to enhancing soil erosion will be nominal in low to moderate burn severity areas. In these areas, the main impacts will be those of loss of ground and canopy cover. The worst-case scenario is the high burn severity areas containing extensive areas of hydrophobic soils and essentially no ground and canopy cover. These ghost town areas exhibit increased erosion by raindrop splash and rill formation, increases in quick flow and peak flow, larger watershed response ratios, and greater erosion and sedimentation rates. These erosion and watershed responses could be due to either the presence of hydrophobic soils (DeBano, 2000) or loss of ground and canopy cover (Foxx, 1984; Allen, 1996). Because most fires in the US do not burn as hot as the Cerro Grande Fire, the 14,511 acres of the Cerro Grande Fire in this high burn severity category represent a unique opportunity to study the relative contributions of these two factors to heightened soil erosion. However, the results of the Enhanced USLE Approach imply that predicting soil erosion on the basis of ground and canopy cover reductions produces better spatial resolution than the BAER Team Approach, which relies heavily on the arbitrarily-selected correction factors for hydrophobic soils.

The soil loss estimates the Enhanced USLE Approach made bracketed the BAER Team results and gave a larger range in soil erosion values. These values seem to match comparable estimates of predicted runoff that the Water Quality and Hydrology Group at LANL is currently making for each watershed, as well as the occurrence and magnitude of several catastrophic runoff events that followed the Cerro Grande Fire. This result supports the idea that the Enhanced USLE Approach allows for: cost-effective spatial resolution of conservation measures that can be immediately applied to burned areas within the path of the Cerro Grande Fire, potential improvements on the methods that future BAER Teams can use, and an improved evaluation of the kind of information that should be in a facility's natural resources database.

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Table 1. Modification of Santa Fe National Forest TES map units for hydrophobic soils for major vegetation types previously surveyed (Balice, 1998).

Vegetation Type	Micro-climate Vegetation Modifier	USLE Potential Soil Erosion Rate Multiplier
Mixed Conifer Forest	Moist Shrub Understory	1.8
Mixed Conifer Forest	Grass-Shrub Understory	1.3
Mixed Conifer Forest	Grass Understory	1.1
Ponderosa Pine Forest	Shrub Understory	2.5
Ponderosa Pine Forest	Grass Understory	1.8
Ponderosa Pine/Pinyon/Juniper	-	1.2

Table 2. R Factor estimates for various annual precipitation zones in Los Alamos County (Numbers in parentheses represent values expressed in US Customary Units of (hundreds of ft-T)(in) A^{-1} $hr^{-1}yr^{-1}$).

Annual Precipitation (cm)	**R Factor (MJ mm ha^{-1} h^{-1} yr^{-1})**
36-41	594 (35)
41-46	749 (44)
46-51	965 (57)
51-56	1,219 (72)
56-61	1,506 (88)
61-66	1,825 (107)
66-71	2178 (128)

Table 3. Wischmeier (Wischmeier, 1974) and regression models used to predict C Factor (Y) as a function of ground cover (X) for each habitat type.

			Regression model constants			Regression statistics	
Habitat type	**Wischmeier model**	**Regression model used to predict C Factor**	**a**	**b**	**c**	**R^2**	**Standard Error**
Grass	no canopy cover, no compacted duff	$Y^{0.5} = a + bX$	6.52	-0.061		0.98	2.71
Pinyon Juniper on mesa tops	0.5 m short brush/weeds, 25% canopy cover, no compacted duff	$Y = a + bX^{0.5}$	35.9	-3.55		1.00	0.26
Shrub	2 m short brush/weeds, 25% canopy cover, no compacted duff	$Y = a + bX^{0.5}$	35.9	-3.55		1.00	0.26
Shrub	2 m short brush/weeds, 75% canopy cover, no compacted duff	$Y = a + bX^{0.5}$	28.6	2.72		1.00	0.63
Ponderosa Pine	4 m trees, 25% canopy cover, compacted duff	$Y = a + b\exp^{(-X/c)}$	-.0.72	42.6	26.9	1.00	0.42
Ponderosa Pine	4 m trees, 75% canopy cover, compacted duff	$Y = a + b\exp^{(-X/c)}$	-0.66	36.5	28.0	1.00	0.55
Aspen, Spruce-Fir, Mixed conifer	4 m trees, 75% canopy cover, no compacted duff	$Y = a + bX^{0.5}$	35.8	3.55		1.00	0.26

Table 4. Annual soil erosion rates by watershed before and after the Cerro Grande Fire using the BAER Team and Enhanced USLE Approaches (Numbers in parentheses represent annual soil erosion rates expressed in US Customary units of t A^{-1} yr^{-1}).

	Annual soil erosion rate (t ha^{-1} yr^{-1})			
	Pre-Cerro Grande Fire		Post-Cerro Grande Fire	
Watershed	**BAER Team Approach**	**Enhanced USLE Approach**	**BAER Team Approach**	**Enhanced USLE Approach**
Chupaderos Canyon	30,155 (13,450)	1,622 (723)	133,598 (59,589)	47,800 (21,320)
Canada del Buey	7,008 (3,126)	147 (65)	8,674 (3,869)	386 (172)
Frijoles Mesa Canyon	402 (179)	13 (6)	472 (211)	32 (14)
Frijoles Canyon	24,928 (11,119)	1,255 (560)	77,970 (34,777)	20,773 (9,265)
Guaje Canyon	184,051 (82,092)	15,504 (6,915)	991,509 (442,243)	713,273 (318,142)
Garcia Canyon	54,099 (24,130)	5,250 (2,341)	358,757 (160,016)	235,053 (104,841)
Los Alamos Canyon	60,045 (26,782)	10,527 (4,695)	731,513 (326,277)	1,110,969 (495,526)
Mortandad Canyon	33,479 (14,933)	573 (256)	50,033 (22,316)	1,212 (540)
Pajarito Canyon	71,656 (31,961)	5,596 (2,496)	695,749 (310,325)	545,692 (243,395)
Potrillo Canyon	2,414 (1,077)	66 (29)	2,710 (1,209)	147 (66)
Pueblo Canyon	31,221 (13,925)	1,365 (609)	394,797 (176,092)	231,548 (103,277)
Rendija Canyon	118,814 (52,995)	6,793 (3,030)	1,241,977 (553,959)	832,858 (371,480)
Sandia Canyon	1,018 (454)	38 (17)	1,132 (505)	70 (31)
Santa Clara Canyon	133,660 (59,616)	11,802 (5,264)	934,451 (416,793)	538,633 (240,247)
Canon de Valle	28,496 (12,710)	3,392 (1,513)	127,727 (56,970)	149,463 (66,665)
Water Canyon	40,526 (18,076)	4,540 (2,025)	408,383 (182,151)	369,820 (164,951)
Sum:	821,971 (366,624)	68,482 (30,545)	6,159,451 (2,747,302)	4,797,730 (2,139,933)

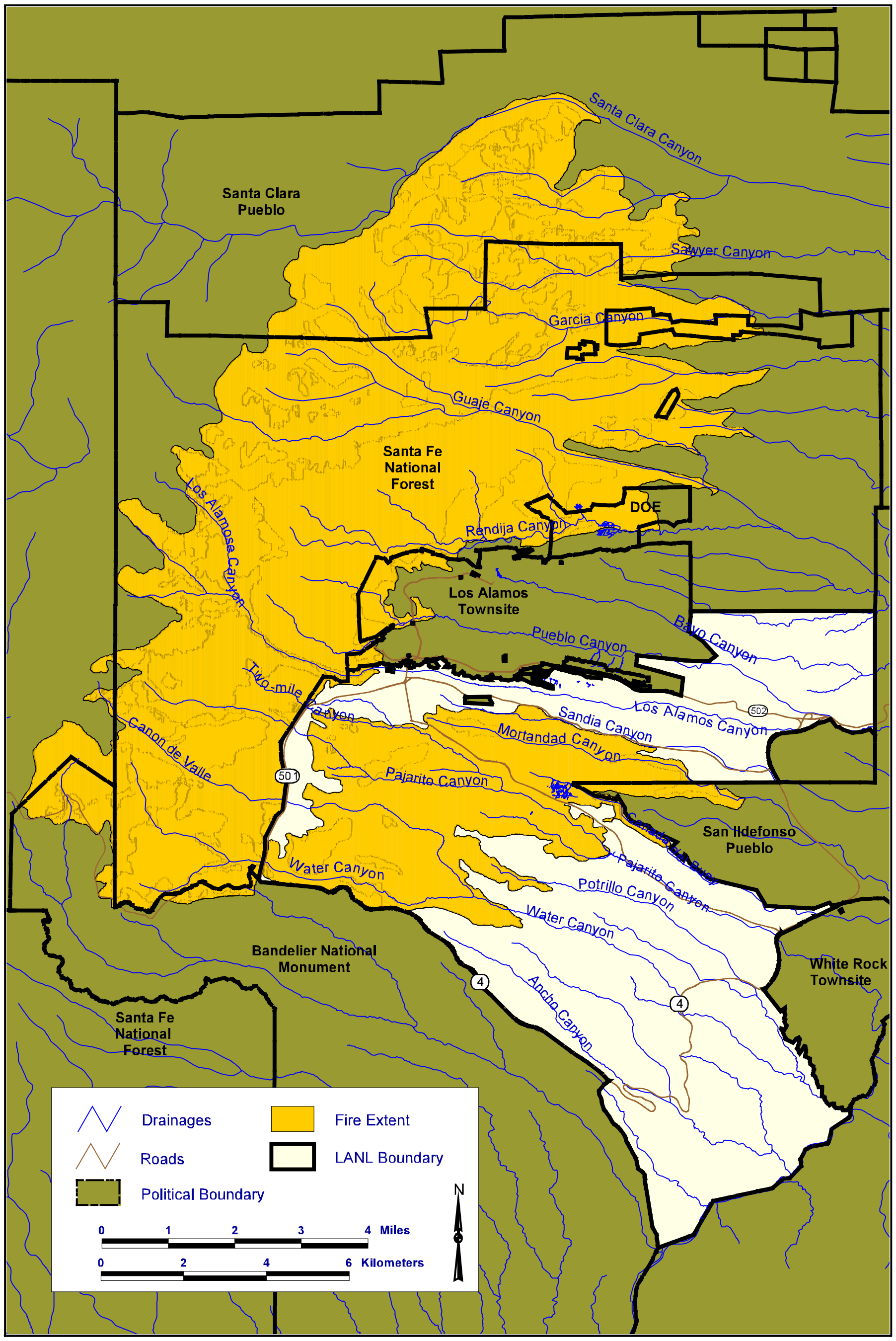

Fig. 1. Location of Los Alamos and Cerro Grande Fire area.

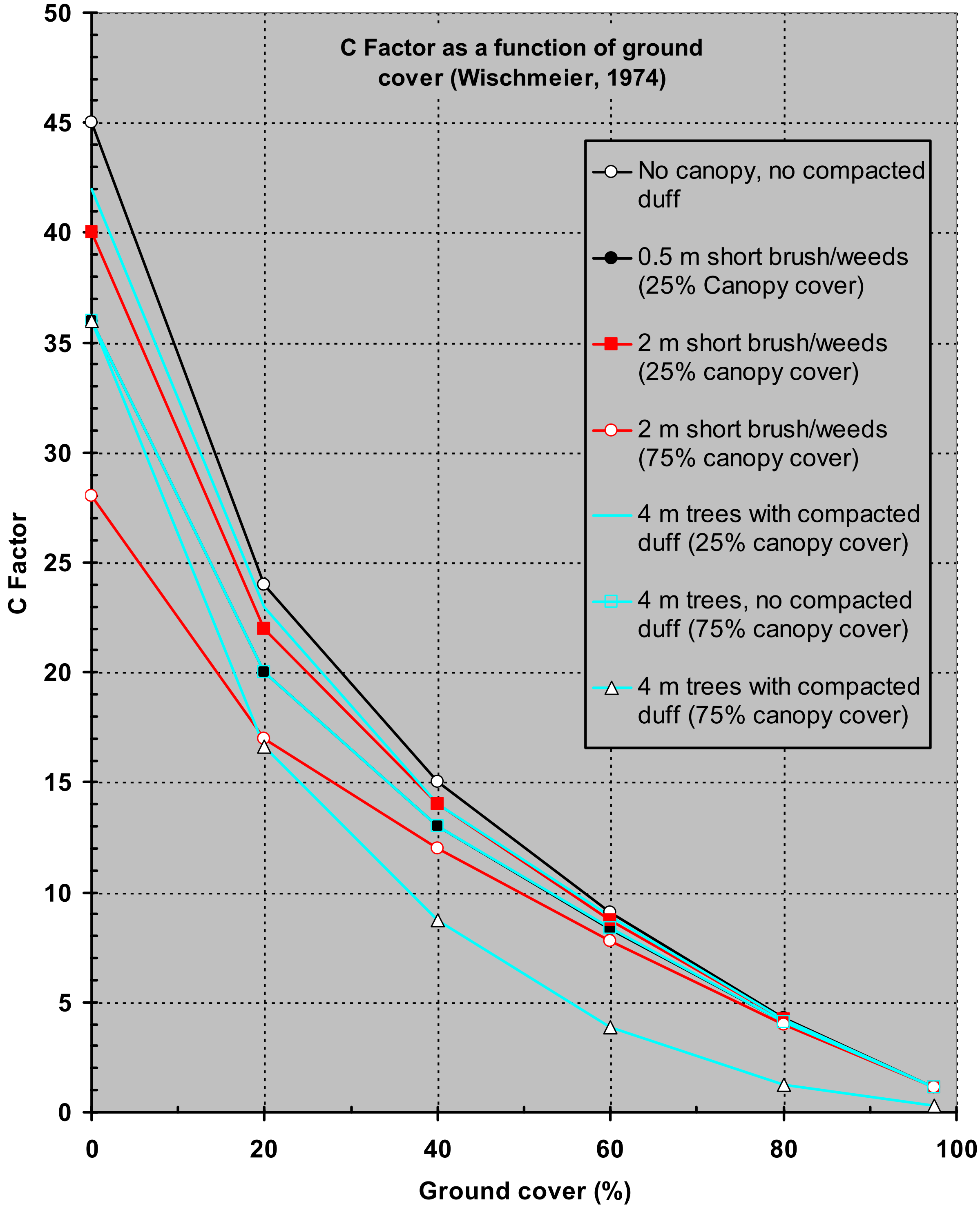

Fig. 2. Cover Management Factor (C) as a function of ground and canopy cover (Wischmeier, 1974).

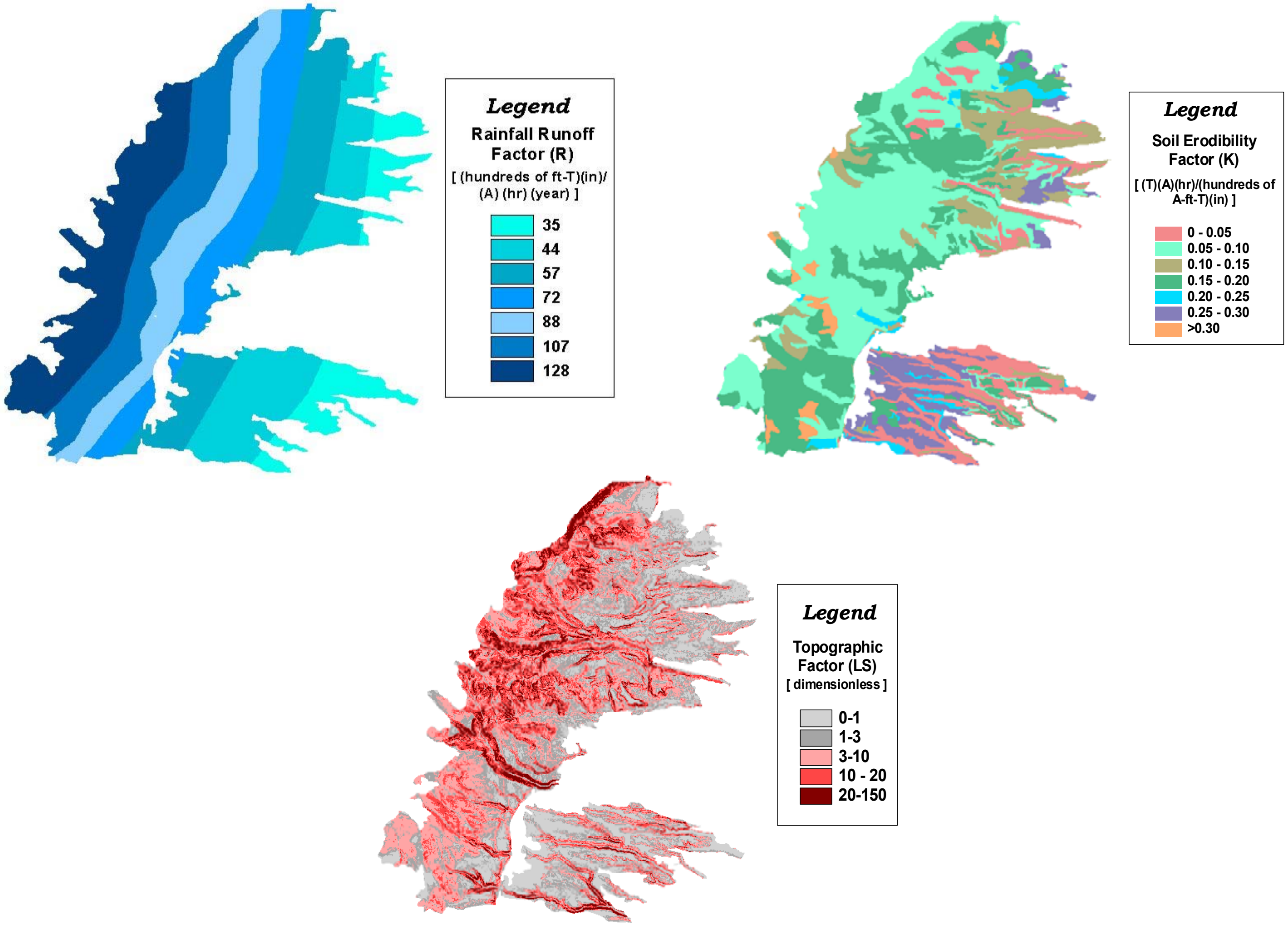

Fig. 3. Maps of the Rainfall Runoff, Soil Erodibility, and Topographic Factors within the Cerro Grande Fire area.

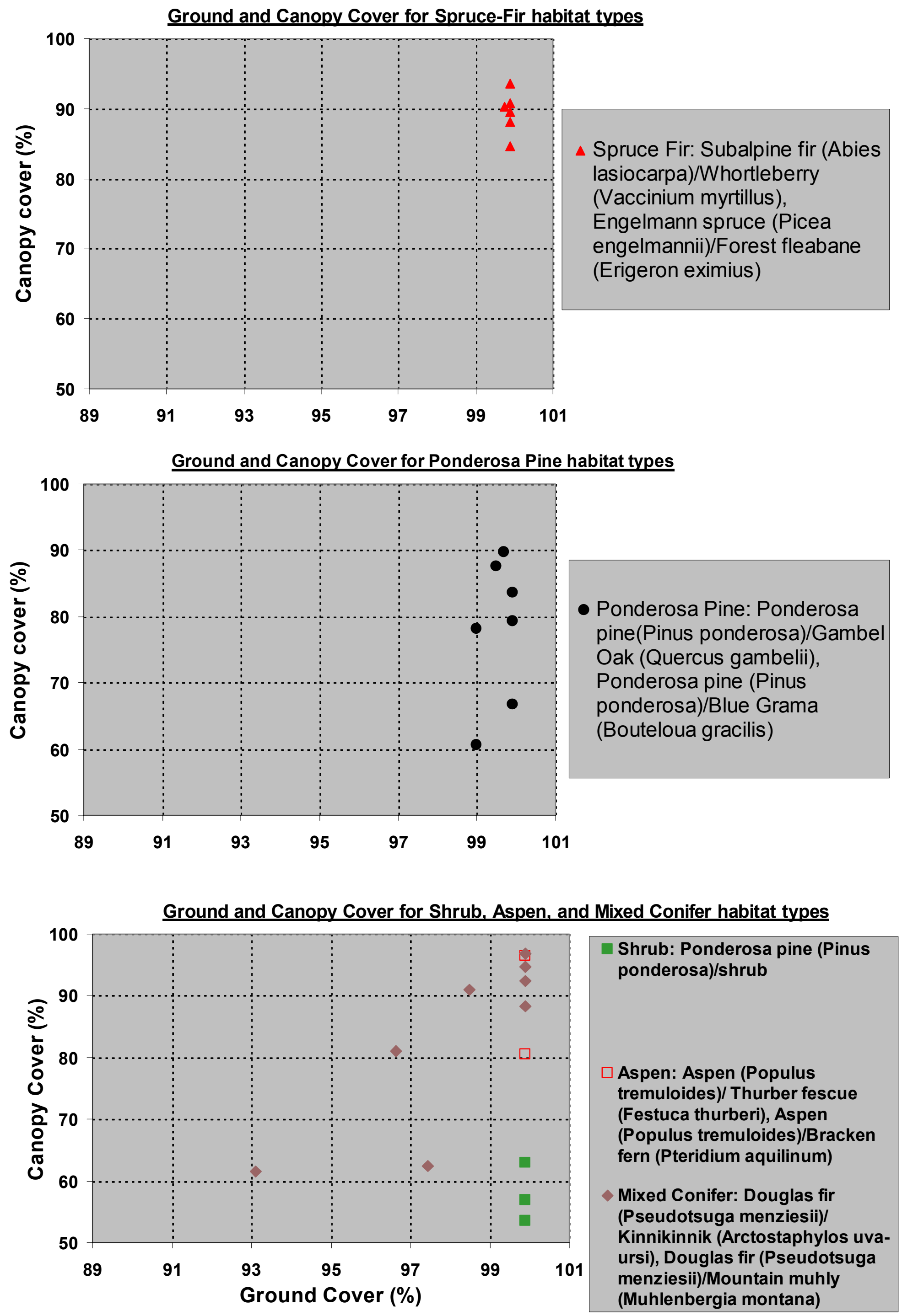

Fig. 4. Ground and canopy cover for Los Alamos field plots.

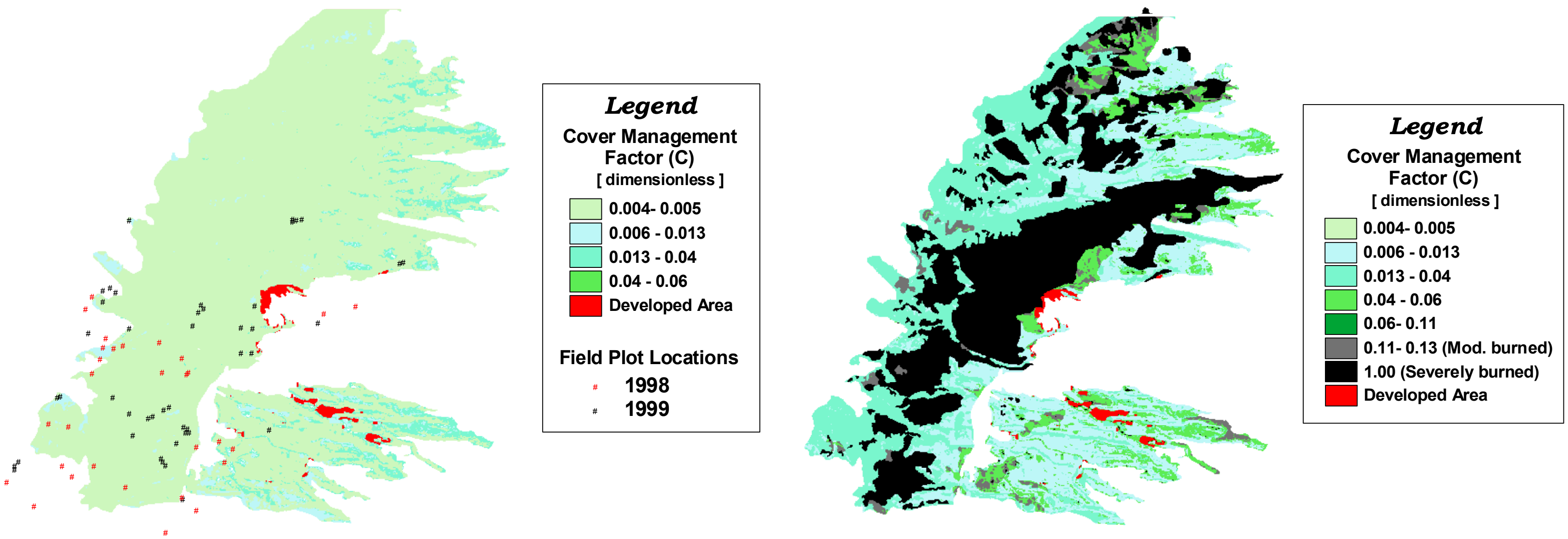

Fig. 5. Maps of the Cover Management Factor used in the Enhanced USLE Method before and after the Cerro Grande Fire.

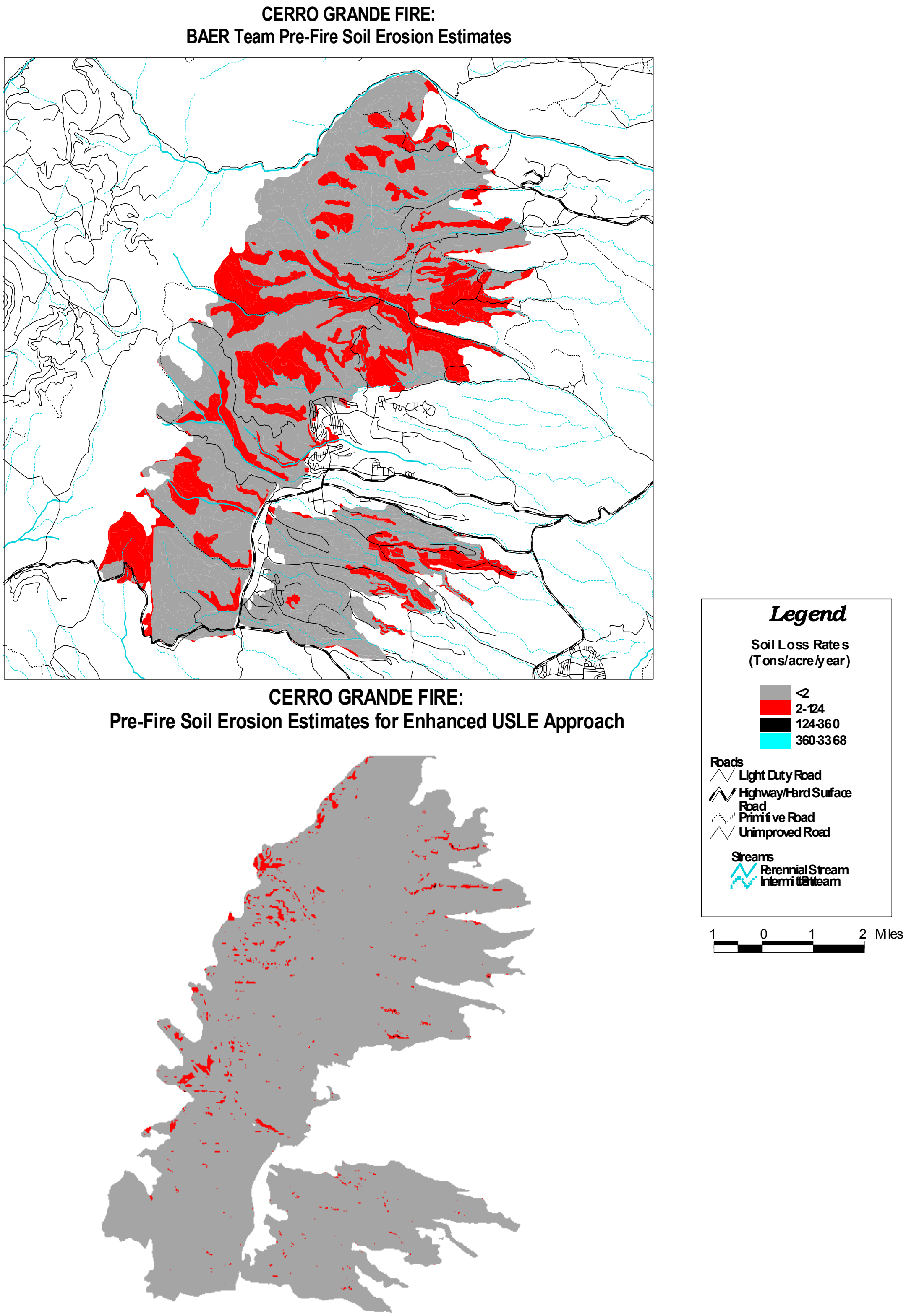

Fig. 6. Soil loss rates evaluated with the BAER Team and Enhanced USLE Methods before the Cerro Grande Fire.

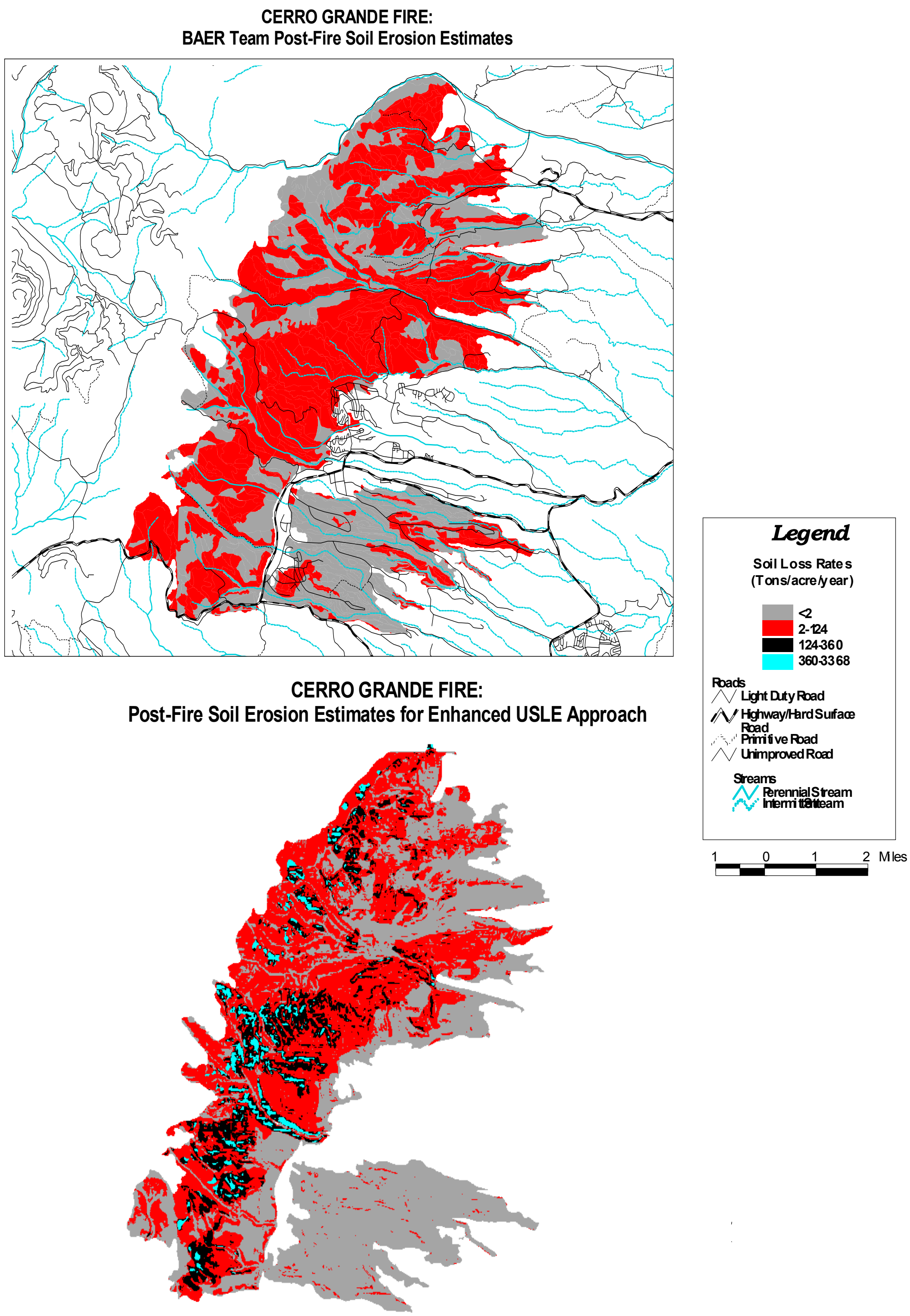

Fig. 7. Soil loss rates evaluated with the BAER Team and Enhanced USLE Methods after the Cerro Grande Fire.